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Neutral hydrogen in nearby elliptical and lenticular galaxies: the continuing formation of early-type galaxies

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ABSTRACT

We present the results of deep Westerbork Synthesis Radio Telescope observations of neutral hydrogen in 12 nearby elliptical and lenticular galaxies. The selected objects come from a representative sample of nearby galaxies earlier studied at optical wavelengths with the integral-field spectrograph SAURON (Spectrographic Areal Unit for Research on Optical Nebulae). They are field galaxies, or (in two cases) located in poor group environments. We detect H I – both in regular discs as well as in clouds and tails offset from the host galaxy – in 70 per cent of the galaxies. This detection rate is much higher than in previous, shallower single-dish surveys, and is similar to that for the ionized gas. The results suggest that at faint detection levels the presence of H I is a relatively common characteristic of field early-type galaxies, confirming what was suggested twenty years ago by Jura based on *IRAS* observations. The observed total H I masses range between a few times 10^6 to just over 10^9 $M_{\odot}$. The presence of regular disc-like structures is a situation as common as H I in offset clouds and tails around early-type galaxies. All galaxies where H I is detected also contain ionized gas, whereas no H I is found around galaxies without ionized gas. Galaxies with regular H I discs tend to have strong emission from ionized gas. In these cases, the similar kinematics of the neutral hydrogen and ionized gas suggest that they form one structure. The kinematical axis of the stellar component is nearly always misaligned with respect to that of the gas. We do not find a clear trend between the presence of H I and the global age of the stellar population or the global dynamical characteristics of the galaxies. More specifically, H I detections are uniformly spread through the $(V/\sigma, \epsilon)$ diagram. If fast and slow rotators – galaxies with high and low specific angular momentum – represent the relics of different formation paths, this does not appear in the presence and characteristics of the H I. Our observations support the idea that gas accretion is common and does not happen exclusively in peculiar early-type galaxies. The links observed between the large-scale gas and the characteristics on the nuclear scale (e.g. the presence of kinematically decoupled cores, radio continuum emission etc.) suggest that for the majority of the cases the gas is acquired through merging, but the lack of correlation with the stellar population age suggests that smooth, cold accretion could be an alternative scenario, at least in some galaxies. In either case, the data suggest that early-type galaxies continue to build their mass up to the present.

Key words: galaxies: elliptical and lenticular, cD. – galaxies: ISM – radio lines: galaxies

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1 INTRODUCTION

The currently favoured paradigm for early-type galaxy formation is the so-called hierarchical formation scenario. It is supported by detailed *N*-body and hydrodynamical simulations, which are able to reproduce the main stellar morphological characteristics and global scaling relations of early-type galaxies (e.g. De Lucia et al. 2006). The role and fate of the gas component, however, is still not well understood. This is partly due to the complexity of understanding gaseous processes (star formation, energetic feedback and reprocessing), and partly because the gas content of early-type galaxies is often thought to be insignificant. Moreover, the parameter space of gas accretion is large, ranging from merging of two large, equal mass gas-rich objects to infall of a tiny gas-rich companion, and perhaps so-called cold accretion, the slow but long-lasting infall of primordial gas (e.g. Keres et al. 2005).

Recent observations of early-type galaxies show that gas is clearly present in these objects, and that gas processes may play a more important role in shaping the stellar properties than previously thought. In a galaxy merger event, the amount of gas involved can have a profound effect on the merger remnant, with gas-rich events leading to more disc-like objects (e.g. Bekki & Shioya 1997; but see Burkert & Naab 2005). This may explain the 'discy' isophote distortions present in many early-type galaxies, and it has been suggested as an explanation of the apparent dichotomy of fast- and slow-rotating galaxies (i.e. galaxies with high and low specific angular momentum; Bender, Burstein & Faber 1992). Dynamically distinct stellar subcomponents are often found in early-type galaxies, and taken as evidence for formation via merging. Connecting a significant star formation event with such a merger has given mixed results, but there are clearly cases where subcomponents of the galaxy are both chemically and kinematically distinct (McDermid et al. 2006), strongly suggesting that external gas has entered the system.

In order to make progress on these issues, high-quality observations of the gas content of early-type galaxies are crucial to allow detailed comparisons with the stellar properties. In the optical, various studies in the recent past have explored the characteristics of the ionized gas in early-type galaxies (Phillips et al. 1986; Buson et al. 1993; Goudfrooij et al. 1994) and found the presence of gas with complex kinematics (e.g. counter-rotating with respect to the stellar component; Bertola, Buson & Zeilinger 1992). However, so far the kinematics and ionization of the gas in early-type galaxies have been studied mostly through long-slit observations, usually along one or two position angles (PAs), which limit the correct determination of the morphology and dynamical structure of the ionized gas. The recent systematic survey based on observations with the panoramic integral-field spectrograph SAURON (Spectrographic Areal Unit for Research on Optical Nebulae) shows that these objects display a variety of line-strength distributions and kinematic structures which is richer than often assumed (Bacon et al. 2001; de Zeeuw et al. 2002). The survey includes 48 representative nearby early-type galaxies classified as E or S0 in de Vaucouleurs et al. (1991, hereafter RC3). Many examples of minor axis rotation, decoupled cores, embedded metal-rich stellar discs, as well as non-axisymmetric and counter-rotating gaseous discs have been found (Emsellem et al. 2004; Kuntschner et al. 2006; Sarzi et al. 2006).

At radio wavelengths, our knowledge about the neutral hydrogen content of early-type galaxies is also changing. This is partly due to the growing number of cases where H I has been imaged – instead of using only single-dish data – and information about the morphology and the detailed kinematics of the gas is now available. Many H I-rich early-type galaxies are now known (e.g. Schiminovich et al. 1995; Morganti et al. 1997; van Gorkom & Schiminovich 1997; Sadler et al. 2000; Balcells et al. 2001; Oosterloo et al. 2002 and references therein; Oosterloo et al. 2004, 2005). The large amount of neutral hydrogen detected around some of these galaxies (up to more than 10^{10} M$_\odot$) is often distributed in huge (up to 200 kpc in size) regularly rotating discs or rings. The flat rotation curves of the discs indicate the existence of large haloes of dark matter. Given their regular appearance, these discs must be relatively old (several $\times 10^9$ yr). Although an external origin of the H I has been suggested already in several earlier studies (e.g. Knapp, Turner & Cunniffe 1985), the imaging of the kinematics of such structures opens the possibility of studying in detail how these galaxies have formed. In particular, although major mergers and small-companion accretions are clearly at the origin of some of the H I structures observed (e.g. Serra et al. 2006), recent work has shown that smooth cold gas accretion (e.g. Macció, Moore & Stadel 2006) can also play an important role and should, therefore, be taken into account.

The shallow H I surveys available so far are, however, able to study only the most extreme H I-rich early-type galaxies. Much deeper observations are needed to explore the complete H I mass distribution of early-type galaxies. Furthermore, the study of H I in these systems has lacked the important combination of having both the H I data and multislit or integral-field optical spectroscopy available for a significant number of objects. For these reasons, we have performed deep H I observations, using the recently upgraded Westerbork Synthesis Radio Telescope (WSRT), of a subsample of E and S0 galaxies in the SAURON representative survey. We present the results here. We describe the sample selection and the WSRT observations in Section 2. In Section 3, we discuss the H I maps, and we compare with earlier H I surveys in Section 4. A discussion of the relation between the presence of H I and of a radio-loud active galactic nucleus (AGN) is given in Section 6. We investigate the relation with the characteristics of the stellar component and the ionized gas in Section 5, and comment on the origin of the neutral gas in Section 7. We summarize our conclusions in Section 8. In Appendix A, we report the serendipitous discovery of a megamaser in the field of NGC 4150.

2 SAMPLE AND H I WSRT OBSERVATIONS

The SAURON sample contains 24 galaxies classified as E in the RC3, and another 24 classified as S0. They are divided equally between so-called 'field' and 'cluster' environments, and cover a factor of 50 in total luminosity and the full range of ellipticity (de Zeeuw et al. 2002). We selected the 12 E and S0 objects with declination $\delta > 23^\circ$, in order to have good spatial resolution with the WSRT. The majority of the selected galaxies are genuine field galaxies, with two cases (NGC 4150 and NGC 4278) are located in poor group environments. None of them reside in a dense cluster environment.

The specifics of the WSRT observations are listed in Table 1. The observations were made using a band of 20 MHz (corresponding to $\sim$4000 km s^{-1}), centred on the frequency of the redshifted H I, and sampled with 1024 channels. One object, NGC 2685, had already been observed with a similar setup by Józsa, Oosterloo & Klein (2004a) and Józsa (2006). We did not re-observe this galaxy but refer to their results.

The calibration and analysis were done using the MIRIAD package. The data cubes were constructed with a robust (Briggs 1995) weighting equal to 0, or with natural weighting for the faintest cases. The cubes were made by averaging channels in groups of two, followed by Hanning smoothing so that a velocity resolution of 16 km s^{-1}

Table 1. Summary of observations and properties of the galaxies in the sample. (1) Galaxy identifier. (2) Systemic velocity at which we centred the H I observation band. (3) Hubble type (NED). (4) Galaxy distance from the surface brightness fluctuation (SBF) measurements of Tonry et al. (2001). Four galaxies (NGC 2685, NGC 5198, NGC 5308 and NGC 5982) do not have SBF distances. In those cases we used redshift distances from the Lyon-Meudon Extragalactic Database (LEDA). (5) Linear scale. (6) Date of observation. (7) Integration time in hours. (8) Beam. (9) Noise level in the H I cube. (10) Noise level of the continuum image. (11) Contour levels of the total intensity images shown in Fig. 1.

NGC	Type	$V_{\rm centr}$ km s^{-1}	D Mpc	pc/arcsec	Date DD/MM/YY	Int. time h	Beam arcsec × arcsec (°)	Noise H I mJy beam^{-1}	Noise cont. mJy beam^{-1}	H I contours 10^{19} cm^{-2}
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
1023	S0	614	11.4	55	12–17/10/04	4 × 12	21 × 14(1)	0.26	0.026	(2.5), 5, 10, 25, 50
2549	S0	1069	12.6	61	02/01/04	12	60 × 55(0)	0.41	0.034	–
2685	S0	883	15.7	76	12/02-01/03[a]	4 × 12	28 × 25(10)	0.24	–	(5), 10, 25, 50, 100
2768	E	1359	22.4	109	03/01/04	12	33 × 33(-84)	0.47	0.034	1, 2.5, 5, 10, 25
3414	S0	1472	25.2	122	2/02/04	4 × 12	45 × 33(9)	0.27	0.026	1, 2.5, 5, 10, 50, 100
4150	S0	219	13.7	67	31/01/04	4 × 12	41 × 34(17)	0.30	0.021	1, 2.5
4278	E	631	16.1	78	04/02/04	4 × 12	28 × 14(11)	0.23	0.037	1, 2.5, 5, 10, 25
5198	E	2531	39.6	192	01/05/04	2 × 12	37 × 35(13)	0.37	0.026	2.5, 5, 10, 25, 50, 100
5308	S0	1985	32.8	159	22/04/04	12	35 × 35(0)	0.58	0.080	–
5982	E	2935	45.7	222	11/09/04	12	36 × 36(79)	0.56	0.043	5, 10
7332	S0	1206	23.0	112	07/09/04	18	46 × 31(6)	0.40	0.043	1, 2.5, 5, 10, 25, 50,100
7457	S0	845	13.2	64	31/08/04	12	39 × 32(15)	0.38	0.038	–

[a]Data taken by G. Józsa and presented in Józsa et al. (2004a) and Józsa (2006).

was obtained. This was done to optimize sensitivity. The rms noise and restoring beam sizes of each cube are given in Table 1.

As a by-product of the observations, the line-free channels were used to obtain an image of the radio continuum of each galaxy. The continuum images were made with uniform weighting. The rms noise and beam of these images are also given in Table 1. Radio continuum emission was not detected in four of the objects, in which cases only upper limits are determined. All the detected continuum sources are unresolved. The peak flux and power of the continuum, or the 3σ upper limits, are given in Table 2.

3 RESULTS

We detect H I in emission in eight (possibly nine, NGC 7332 is an unclear case, see Section 3.2) of the 12 galaxies observed. Three of the detected objects (NGC 1023, NGC 2685 and NGC 4278) were already known to have H I from previous observations (respectively, Sancisi et al. 1984; Shane 1980; Raimond et al. 1981; Lees 1994). Table 2 summarizes the H I morphology, mass and size for every detected object. Three galaxies (NGC 2549, NGC 5308, NGC 7457) are not detected in H I. In these cases the H I mass limits range from a few times 10^6 to at most $10^7\,{\rm M}_{\odot}$.

The measured H I masses (see Table 2) range between a few times 10^6 to just over $10^9\,{\rm M}_{\odot}$. The value for the gas content ($M_{\rm H\,I}/L_B$) ranges from <0.0003 to as high as $0.3\,{\rm M}_{\odot}/{\rm L}_{\odot}$ in the case of NGC 2685. The latter represents a value at the gas-rich end of the distribution characteristic of early-type galaxies (Knapp et al. 1985) and is comparable to that of normal spiral galaxies.

Fig. 1 shows the H I total intensity images. The sizes of the H I structures vary between 30 and 90 kpc with the exception of the tiny H I disc detected in NGC 4150 that is only 4 kpc in diameter and the small cloud in NGC 5982. The typical peak column density is at most a few times 10^{20} cm^{-2} (see contour levels in Fig. 1). As already found from the H I observations of other early-type galaxies (see e.g. van Driel & van Woerden 1991; Morganti et al. 1997; Serra et al. 2006) these values of the column density are lower than the critical surface density for star formation proposed by Kennicutt (1989). Although this result excludes the presence of widespread star formation activity, local small regions of star formation can still be present.

Most of the continuum sources associated with the observed galaxies are too weak to be used to detect H I in absorption. The only exception is NGC 4278, where nevertheless no H I absorption was found. Given the low spatial resolution of our observations, H I absorption, even if present, is likely filled up with the H I in emission present in this galaxy.

We divide the observed H I structures in three main groups: (1) regularly rotating, disc-like H I emission, (2) offset clouds or tails and (3) complex distribution. The presence of regular disc-like structures is as common as H I in offset clouds and tails around galaxies. Fig. 2 shows examples of position–velocity plots, along one of the main axes, for the most interesting cases. Below, we summarize the H I characteristics for each object, together with relevant information obtained from the SAURON observations. For a more detailed description of the optical characteristics obtained from the SAURON, we refer to the original papers: Emsellem et al. (2004), Kuntschner et al. (2006) and Sarzi et al. (2006).

3.1 Regular H I structures

In four galaxies (NGC 2685, NGC 3414, NGC 4150 and NGC 4278), the H I appears to be distributed in a relatively regularly rotating structure.

NGC 2685, also known as the Spindle galaxy, shows strong, helix-like dust extinction on the north-eastern side and it is a classical polar ring (Whitmore et al. 1990). The kinematics of the H I clearly change with radius. In the inner part the kinematical major axis is perpendicular to the photometric major axis, while at large radius, the kinematical major axis is aligned with the photometric major axis. The two position–velocity diagrams in Fig. 2 show this very clearly. A tilted-ring analysis (Józsa et al. 2004a; Józsa 2006) indicates that the H I is actually one single structure that is polar in the inner regions while at a radius of about 1 arcmin it warps about 90° to become coplanar with the optical galaxy. Józsa et al. (2004a) suggest that the H I could be a disc that forms from a single accretion event under the influence of a tumbling triaxial halo (Peletier

Table 2. Further properties of the galaxies and measurements based on our radio observations. (1) Galaxy identifier. (2) Hubble type (NED). (3) Total K-band apparent magnitude from the 2 Micron All Sky Survey (2MASS) Extended Source Catalogue (Jarrett et al. 2000). (4) Total mass in H I. (5) Ratio of total mass in H I and the absolute B-band luminosity L_B. (6) Ratio of total mass in H I and the absolute K-band luminosity L_K. (7) Diameter of the H I distribution. (8) Continuum flux (or 3σ upper limits) at 1.4 GHz. (9) Total radio power at 1.4 GHz. (10) References: (a) Sancisi et al. (1984); (b) Shane (1980); (c) Józsa et al. (2004a); (d) Józsa (2006); (e) Raimond et al. (1981); (f) Lees (1994).

NGC	Type	$K_{\rm T}$ mag	$M_{\rm H\,I}$ $M_\odot$	$M_{\rm H\,I}/L_B$	$M_{\rm H\,I}/L_K$	Diam H I kpc	$S_{1.4\,\rm GHz}$ mJy	$\log P_{1.4\,\rm GHz}$ W/Hz	H I References
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1023	S0	6.24	2.1×10^9	0.046	0.025	92	0.4	18.7	a
2549	S0	8.05	$<2.0 \times 10^6$	<0.00043	<0.00010	–	<0.1	<18.3	
2685	S0	8.35	1.8×10^9	0.27	0.078	41	2[a]	19.8	b, c, d
2768	E	7.00	1.7×10^8	0.0038	0.0010	60	10.9	20.8	
3414	S0	7.98	1.6×10^8	0.0096	0.0019	26	5.0	20.6	
4150	S0	8.99	2.5×10^6	0.00078	0.00025	4	0.8	19.2	
4278	E	7.18	6.9×10^8	0.039	0.0097	37	336.5	22.0	e, f
5198	E	8.90	6.8×10^8	0.030	0.0077	70	2.4	20.6	
5308	S0	8.36	$<1.5 \times 10^7$	<0.00064	<0.00015	–	<0.24	<19.5	
5982	E	8.15	3.4×10^7	0.00060	0.00014	–	0.5	20.1	
7332	S0	8.01	6.0×10^6	0.00038	0.00009	–	<0.13	<18.9	
7457	S0	8.19	$<2.0 \times 10^6$	<0.00032	<0.00010	–	<0.11	<18.5	

[a]Radio continuum from NRAO VLA Sky Survey (NVSS).

& Christodoulou 1993). The SAURON data show the presence of ionized gas (Hβ and [O III]), mostly concentrated along the photometric minor axis. The kinematics of the ionized gas and of the stars is shown in Fig. 3. This figure clearly shows that the ionized gas has the same kinematics as the very inner regions in the H I data. The stellar populations are moderately young and have solar metallicity. CO (J = 2–1 and 1–0) emission was detected by Schinnerer & Scoville (2002). They find four molecular cloud associations in the western and eastern regions of the galaxy, close to the brightest Hα and H I peaks in the polar ring. The CO and H I line velocities agree, which indicates that the CO emission also originates from the polar ring.

NGC 3414 is another interesting object. A rotating structure of $\sim$3.5 arcmin ($\sim$29 kpc) and $\sim 10^8\,M_\odot$ of neutral hydrogen is observed. The rotation axis of the H I is misaligned with the photometric axis by $\sim 44^\circ \pm 5^\circ$. The H I position–velocity diagram (Fig. 2) suggests the presence of two kinematical components, a fast (at least in projection) inner one and a slower, or possibly more face-on, extended outer structure. In the inner region, observed with SAURON, the stellar kinematics shows a kinematically decoupled core (KDC). The ionized gas has a complex morphology showing a smoothly twisting velocity field such that the rotation axis aligns with the photometric major axis at large radii, but it almost aligns with the KDC within the central 5-arcsec radius (see also Fig. 3). The rotation of the H I lines up very well with that of the outer ionized gas. The stellar populations are old and have solar metallicity.

NGC 4150 shows the faintest and smallest rotating H I disc detected, with only a few $\times 10^6\,M_\odot$ of neutral hydrogen. The size of the H I disc is about 1 arcmin ($\sim$4 kpc). A cloud of low column density H I is also observed about 1 arcmin from the galaxy, without an obvious optical counterpart. NGC 4150 is also detected in CO (Welch & Sage 2003; Leroy et al. 2005) and the estimated molecular gas content is $\sim 3.0 \times 10^7\,M_\odot$. From the SAURON data, a small stellar KDC is observed in the central 2 arcsec. The ionized gas follows the outer stellar kinematics, with a possible central disc. The stellar population is globally rather young with a strong contribution of young stars in the central few arcseconds.

NGC 4278 was known to have an extended regular disc of H I (Raimond et al. 1981; Lees 1994), but our data show this disc and its kinematics in much more detail. The new data also show that two faint tail-like structures exist at large radius (see Fig. 1). The kinematics of the H I is regular. The position–velocity diagram taken along PA 80° (Fig. 2) shows large modulations of the velocities indicating that large deviations from a flat disc in circular rotation occur. The SAURON data show strong ionized gas, with a large-scale twisted rotation field, rotating in the same sense as the stars, but misaligned by $\sim 20^\circ$–70° (see also Fig. 3). Also in this galaxy, the kinematics of the H I and the ionized gas match very well, and both are misaligned with the stellar kinematics and the photometric axes. The stellar population is old and has near-solar metallicity.

3.2 Neutral hydrogen offset from the galaxy

In three objects (NGC 2768, NGC 5198, NGC 5982) most of the H I is found in clouds/tails offset from the centre of the optical galaxy (see Fig. 1). These H I features do not have an obvious stellar counterpart. They have velocities that are very close (within 300 km s^{-1}) to the systemic velocity of the target galaxy. They are, therefore, likely physically associated with the galaxy.

In NGC 2768, most of the H I is detected in a tail-like system at about 16 kpc north-east from the centre. However, some faint H I emission is also present inside the optical boundaries. The kinematics suggests that these two features are related. The neutral hydrogen in the cloud shows velocities that range from 1430 to 1510 km s^{-1}, slightly redshifted compared to the systemic velocity of the galaxy (1373 km s^{-1}). This velocity matches that of the ionized gas on this side of the galaxy. Wiklind, Combes & Henkel (1995) detected this galaxy in CO with IRAM, and infer a molecular hydrogen mass of $\sim 2 \times 10^7\,M_\odot$. The ionized gas detected by SAURON rotates around the major axis. The rotation is perpendicular to that of the stars, and the stellar population is old.

In NGC 5198, we detect H I both $\sim$2 arcmin ($\sim$23 kpc) north and $\sim$4 arcmin ($\sim$46 kpc) south of the galaxy. The current data are not deep enough to see whether these are actually part of a single, large gaseous structure. However, it is interesting that the systemic velocity of the galaxy is exactly in between that of the two H I clouds. The SAURON data show a central stellar KDC misaligned with the outer rotation. The ionized gas is mostly detected in the central few

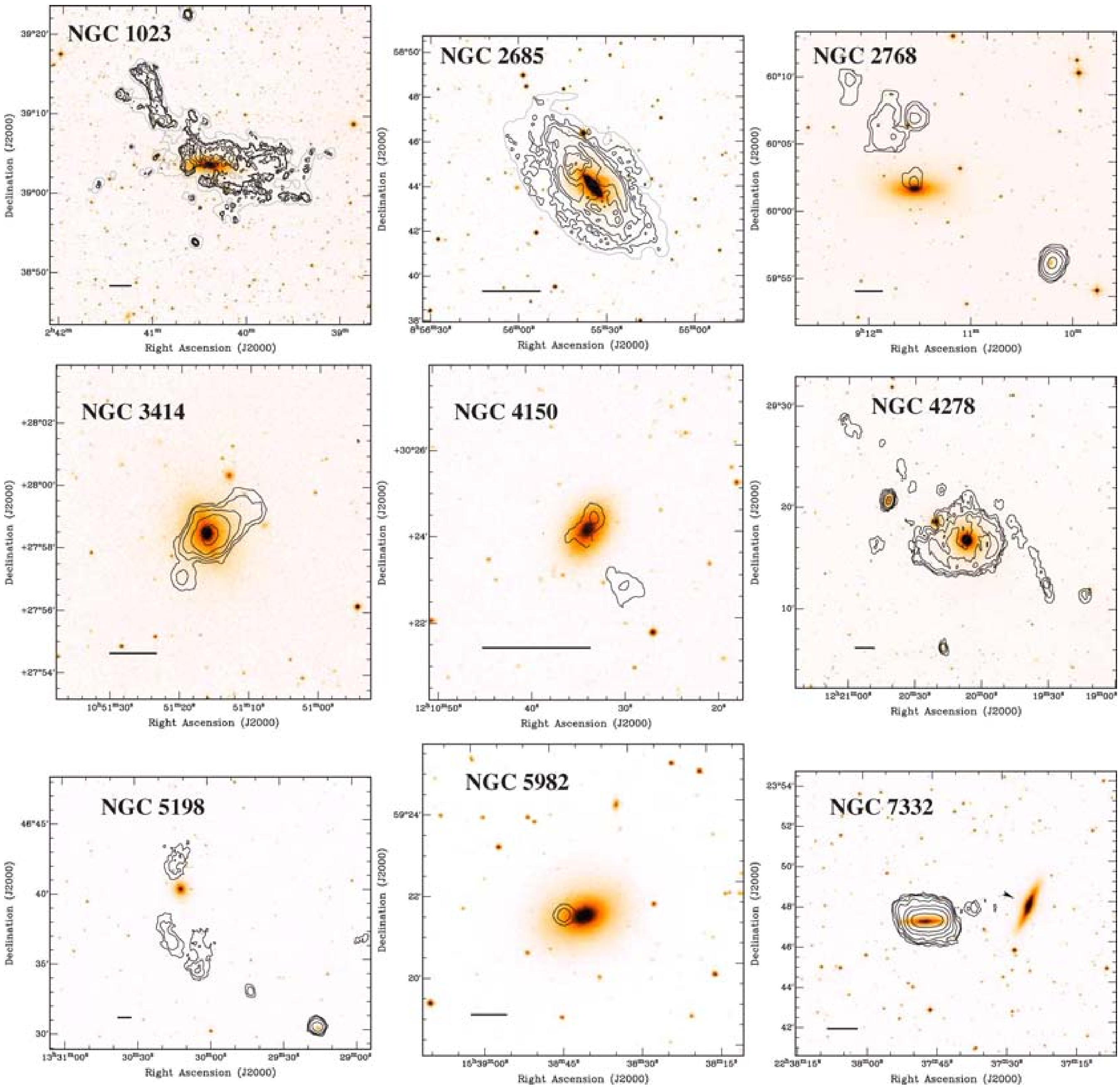

Figure 1. Total H I intensity images (contours) superimposed on to Digital Sky Survey optical images of the detected galaxies. Grey contours in the figures of NGC 1023 and NGC 2685 correspond to the emission detected from lower resolution data. The contour levels are given in Table 1 with the grey contour given in parenthesis. The 10-kpc linear scale is given in every plot. NGC 7332 is indicated with an arrow. Further information on the H I in NGC 2685 can be found in Józsa et al. (2004a) and Józsa (2006).

arcseconds. However, the ionized gas does also extend to the north, and hence could be related to the H I structure. The ionized gas occupies a disc-like structure which is perpendicular to the central KDC, and counter-rotates with respect to the outer rotation. The stellar population is old.

In NGC 5982, a very small blob of H I appears just offset ($\sim$6 kpc) from the galaxy centre with a velocity of $\sim$2830 km s^{-1}, about 200 km s^{-1} lower than the systemic velocity. The SAURON data show a small amount of ionized gas and an apparent KDC. The central gas rotates in the same sense as the KDC. The stellar population is old.

For NGC 7332, an H I cloud is detected *between* this galaxy and the H I-rich companion galaxy NGC 7339. The cloud of neutral hydrogen is located about 3 arcmin ($\sim$14 kpc) from the centre of NGC 7332 (see Fig. 1). The velocity of the H I cloud ($\sim$1250 km s^{-1}) is roughly similar to that of the western side of the H I disc of the companion galaxy NGC 7339 but is also similar to the velocities of the ionized gas measured in the eastern side of the NGC 7332. The velocity of the H I cloud is, however, quite different from the anomalous high-velocity ($\sim$300 km s^{-1} around the systemic velocity) ionized gas detected on the southern side of the galaxy centre in NGC 7332 (Falcón-Barroso et al. 2004). The neutral hydrogen is

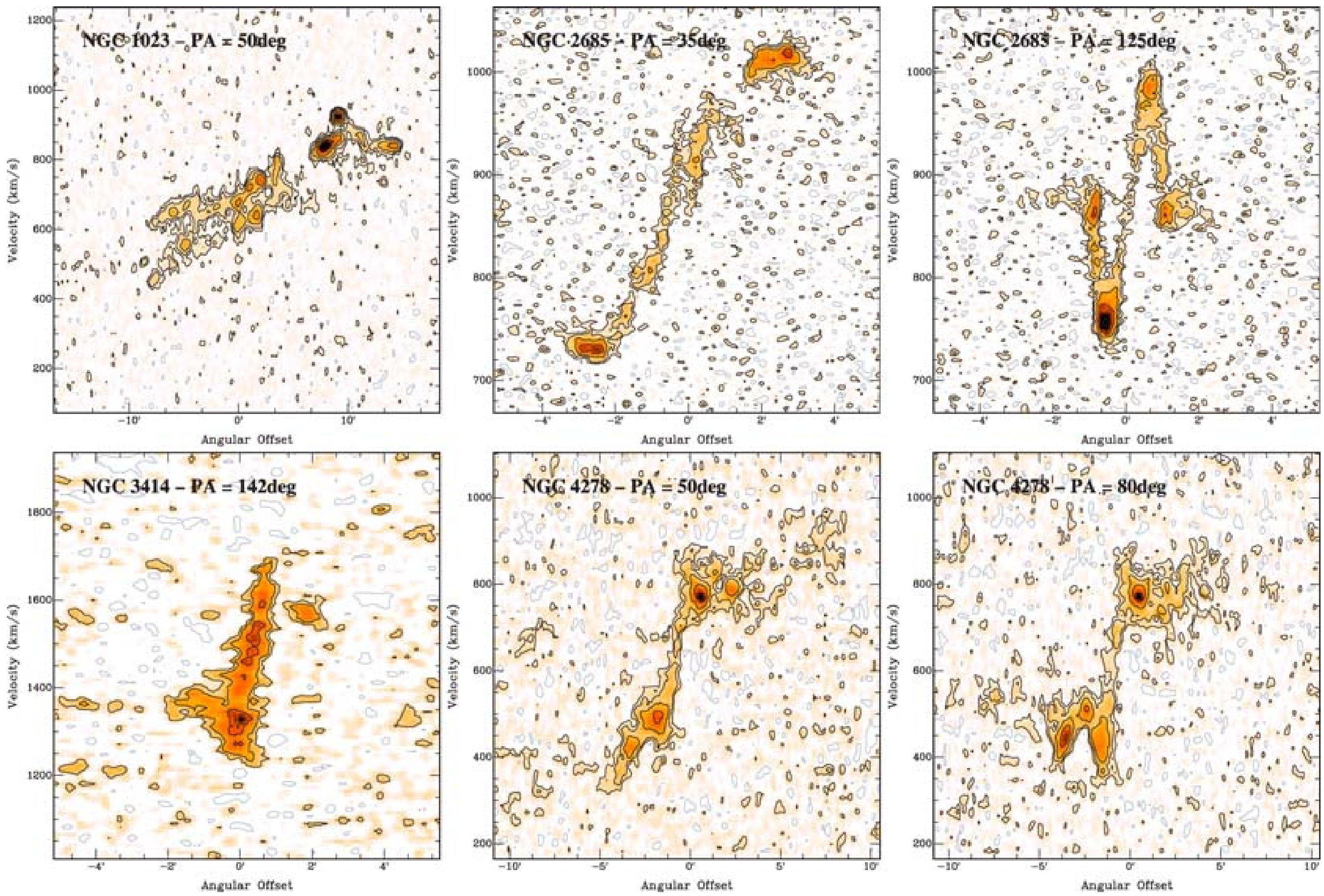

Figure 2. Position–velocity plots of some of the detected galaxies. Contours levels are the following: NGC 1023: −0.32, 0.32:0.1 × 2 mJy beam^{-1}; NGC 2685: −0.54, 0.54:0.1 × 2 mJy beam^{-1}; NGC 3414: −0.25, 0.25:0.01 × 2 mJy beam^{-1}; NGC 4278: −0.21, 0.21:0.01 × 2 mJy beam^{-1}.

likely to be a signature of some interaction between the two galaxies. This interpretation is consistent with evidence found from the SAURON data and from Howell (2006). The stellar kinematics derived by SAURON shows regular rotation, with a small KDC within the central 3 arcsec. The ionized gas is complex, with some regularly rotating structure in [O III] within the central 10 arcsec, which seems to lead on to a larger-scale structure rotating around the long axis (misaligned by 90° to stellar rotation). The stellar population is young. NGC 7332 has been also detected in CO emission by Welch & Sage (2003) and they estimate an upper limit to the molecular hydrogen content of 4.2×10^7 M$_\odot$.

3.3 Complex H I kinematics

The galaxy NGC 1023 has a very extended and complex neutral hydrogen distribution. This H I has been studied in detail by Sancisi et al. (1984). Our observations are a factor of 5 deeper and have much better spatial and velocity resolution. The morphology of the H I (see Fig. 1), however, does not reveal any major surprises compared to the study of Sancisi et al. (1984). On large scales, the H I appears, to first order, to be rotating around the galaxy. However, double-peaked profiles are observed throughout the main body of H I (see Fig. 2), showing that large, systematic deviations from circular rotation occur, while small components with opposite velocity gradients exist. Sancisi et al. (1984) describe the distribution of H I as reminiscent of the tails and bridges found in interacting galaxies and this object may represent an example of a merger in an intermediate stage when the gas is still in the process of settling. Indeed, one of the brightest clouds in the H I distribution coincides with a faint optical companion. The H I is very clumpy, quite different in character from what we observe in the other galaxies. Welch & Sage (2003) estimate an upper limit to the molecular gas mass of 4.9×10^7 M$_\odot$. From the SAURON data, the stellar kinematics of NGC 1023 shows a small but steady twist in the rotation axis across the SAURON field, consistent with the presence of a large stellar bar. The ionized gas is patchy, although seems to rotate in a similar sense as stars and the H I. No obvious dust features are observed. Finally, the stellar population is old with a slightly supersolar metallicity.

3.4 Undetected H I galaxies

For completeness, we briefly summarize the properties (in particular the optical properties derived from the SAURON data) of the three galaxies undetected in H I.

NGC 2549: the ionized gas shows a disc-like structure in the central few arcseconds which is aligned with the stars, but has an irregular distribution at larger radii, showing perpendicular rotation to the stars and a filamentary structure. The stellar populations are of intermediate age and have supersolar metallicity.

NGC 5308 also has very discy stellar kinematics, with an additional thin, edge-on disc in the central 5 arcsec. No emission-line

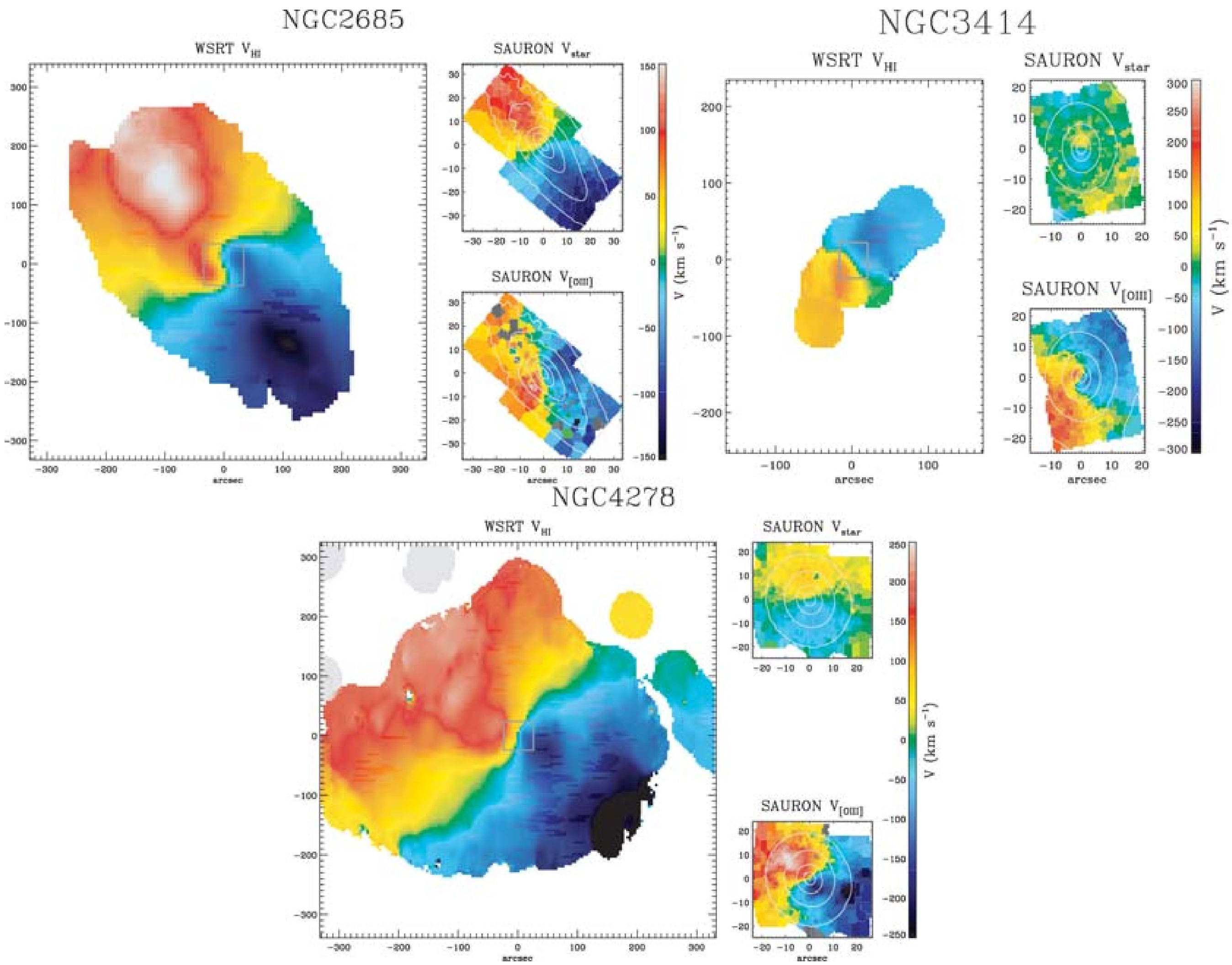

Figure 3. Velocity fields of the neutral hydrogen, ionized gas and stars for three of the four galaxies where regular H I discs have been detected: NGC 2685, NGC 3414 and NGC 4278.

gas was detected with SAURON. The stellar populations are old with solar metallicity.

NGC 7457 is a regularly rotating flattened object, with a small KDC inside the central 3 arcsec. Not much ionized gas was detected; it has irregular structure at large radius, and a compact central rotating component, seemingly aligned with the KDC. The stellar populations in this galaxy are quite young and have solar metallicity. Observations of CO are reported by Welch & Sage (2003), which resulted in an estimated upper limit of 3.3×10^7 $M_{\odot}$ for molecular hydrogen.

4 COMPARISON WITH OTHER H I SURVEYS

The survey of H I in emission presented here represents one of the few available so far for a representative sample of regular early-type galaxies, where both imaging and kinematics of the gas is obtained and where also detailed optical spectral maps are available. Most of the previous H I surveys have used single-dish observations (see e.g. Huchtmeier, Richer & Bohnenstengel 1983; Knapp et al. 1985). A summary of the detection rates is given in van Gorkom & Schiminovich (1997) and Knapp (1999) as well as in other papers (Roberts et al. 1991; Bregman, Hogg & Roberts 1992; Huchtmeier, Sage & Henkel 1995). Although the morphological classification is always a source of uncertainty, these authors estimate the detection rate for field E and S0 galaxies to be 5 and 20 per cent, respectively, whilst having a galaxy classified as peculiar greatly enhances the chance of it being detected in H I, with a detection rate of 45 per cent for Pec E and S0 galaxies.

The surprisingly high detection rate of our observations is likely to be due to a combination of the depth that we have reached and the fact that, unlike single-dish surveys, we have imaged the distribution of H I in every galaxy, therefore, being able to associate to our target galaxies even small clouds of H I (such as in the case of NGC 5982). The results of our deep H I imaging survey indicate that, at faint detection levels, *the presence of H I could be a relatively common characteristic of many early-type galaxies in the field*. This is an important result, although it should be verified by a larger sample.

Jura (1986) reported a high detection rate of E and S0 galaxies in the *IRAS* 60- and 100-μ*m* bands, and deduced the presence of cold dust that would presumably be accompanied by cold gas. He estimated that about one-third of the E/S0s (and maybe more) contain of the order of 10^8 $M_{\odot}$ in H I. Our H I masses agree nicely with his prediction, but the detection rate is even higher than he suggested.

The morphologies of the neutral hydrogen found in our survey can be compared with the results from e.g. van Driel & van Woerden (1991). These authors have studied a sample selected from gas-rich S0 galaxies. These galaxies have neutral hydrogen distributed mainly in inner or outer H I rings. The kinematics can be described mainly by circular rotation – with cases of warped distributions – and flat rotation curves. Compared to these results, our deeper survey has shown the presence of other cases where the H I is offset compared to the optical galaxy suggesting a more complex picture of the H I properties of S0 galaxies. In agreement with the results of van Driel & van Woerden (1991), the average H I surface density found is only $\sim 1\,M_{\odot}\,pc^{-2}$, too low to sustain large-scale star formation.

From the selection of early-type galaxies from the cross-correlation of the H I Parkes All-Sky Survey (HIPASS; Barnes et al. 2001) and the RC3 catalogue, together with imaging follow-up using the Australia Telescope Compact Array (ATCA) (Sadler et al. 2000; Oosterloo et al. 2004, 2005), it has been shown that between 5 and 10 per cent of early-type galaxies are extremely gas rich (with H I masses well above $10^9\,M_{\odot}$ and value of $-1 < \log(M_{\rm H\,I}/L_B) < 0$). In about 70 per cent of these H I-rich galaxies, the neutral hydrogen appears to be distributed in extremely large (up to 200 kpc in diameter) disc-like structures that are regularly rotating. At least some of these large discs represent remnants of a major merger event that occurred at least $\sim 10^9$ yr ago (Morganti et al. 1997; Serra et al. 2006). Our much deeper H I study of the nearby SAURON sample provides complementary information. Given the small size of our sample, it is not surprising that such extremely H I-rich systems are not detected. It is interesting to note, however, that, while in the early types detected by HIPASS the H I is mainly distributed in discs – consistent with the results of van Driel & van Woerden (1991), although the HIPASS detects larger structures – the fainter H I structures in the SAURON galaxies appear to have more varied morphologies. This may imply that regular systems mainly occur in very gas-rich early-type galaxies.

From single-dish surveys it appears that peculiar galaxies have a higher detection rate. However, Hibbard & Sansom (2003) did not detect neutral hydrogen in early-type galaxies classified as optically peculiar using the presence of 'optical fine structure' (shell, ripples, plumes etc.). The failure to detect obvious tidal H I features (although with observations not as deep as those presented here) suggests that if these fine structures in early-type galaxies are remnants of disc–galaxy mergers, either the progenitors were gas poor and/or has been converted into other phases. Our sample (and indeed the SAURON parent sample) is formed by regular galaxies where no major peculiarities have been observed (with the possible exception of NGC 2685). Nevertheless, we still have a very high detection rate of H I. This further strengthens the conclusion that the relation between a galaxy being classified as peculiar and the presence of neutral hydrogen is not straightforward.

Finally, it is worth noting that a shallower study of neutral hydrogen in a sample of radio galaxies (Emonts et al. 2006a) has shown that H I emission is detected in 25 per cent of the objects. Interestingly, the most H I-rich structures are associated with galaxies with compact (or small) radio sources, i.e. objects similar to NGC 4278 (see also Emonts et al. 2006b).

5 COMPARISON WITH OPTICAL PROPERTIES

We now consider the H I properties in relation to the optical properties of the galaxies. We concentrate on the observations made with SAURON, which generally cover the central regions of the galaxies out to about an effective radius, corresponding to roughly one or two times the WSRT beam size.

5.1 Neutral hydrogen and the ionized gas

The WSRT observations suggest that ~70 per cent of early-type galaxies in field or in low-density environments have neutral hydrogen. For comparison, the detection rate of ionized gas in the 48 SAURON (cluster and field) galaxies is 75 per cent and it goes up to 83 per cent for field galaxies. Our observations show that all the galaxies where some H I has been detected also have ionized gas associated to them.

Although the linear scales studied with SAURON are very different from those observed with the WSRT, the similar high occurrence of H I and ionized gas suggests that most early-type galaxies have a detectable amount of gas and that a link exists between the two phases (ionized and neutral) of the gas. This is further motivated by the fact that earlier observations of a few galaxies (using long-slit spectroscopy e.g. NGC 3108, Józsa et al. 2004b; and IC 4200, Serra et al. 2006) have found that, despite the different scales involved, the kinematics of the ionized gas and the neutral gas are very similar, suggesting that both gas phases are part of the same structure. The combination of the WSRT data with the optical integral-field spectroscopy available for the SAURON galaxies allows us to study this in more detail.

The panels in Fig. 3 show the velocity fields of the H I of the ionized gas and of the stellar component for three of the four objects in our sample with regular, disc-like H I emission (NGC 2685, NGC 3414 and NGC 4278). We do not show the fourth galaxy where a regular H I disc has been found (NGC 4150) because the very weak H I emission makes it difficult to construct a meaningful velocity field.

The velocity fields of Fig. 3 show that, regardless of the complicated character of the kinematics of the ionized gas in the very central regions (in terms of e.g. kinematical twists; see also Sarzi et al. 2006), the gas kinematics of the outer edges of the regions covered by SAURON nicely match that of the corresponding very inner data points of the H I data. We have traced the PA and the absolute rotation as function of radius using the harmonic-expansion method for analysing two-dimensional velocity maps of Krajnović et al. (2006). The projected rotation curve is defined as $V(R) = b_1(R)$, where b_1 is the amplitude of the cosine harmonic term, and R is the length of the semimajor axis of the best-fitting ellipse along which velocities were extracted. b_1 is related to the circular velocity through the inclination (i) of the H I disc: $b_1 = V_{\rm rot}(R) \times \sin(i)$. The ellipse PA traces the orientation of the maximum rotation on the maps. In Fig. 4, we plot these two quantities for three galaxies with detected large-scale disc-like H I distributions (for which such an analysis is possible) and compare them with the same quantities measured on the corresponding SAURON velocity maps (both of ionized gas and stars). The SAURON data have higher resolution and show specific behaviour on small scales, but on large scales nicely connect to the H I kinematics. The agreement between the ionized and neutral gas is particularly good for the PAs, but the rotation velocity amplitudes are also very consistent. In all three cases the stellar and gas PAs are strongly misaligned. NGC 2685 is a somewhat special case because the orientation of the stellar velocity field corresponds to the orientation of the large-scale H I disc, suggesting an underlying connection between these two components, while the central warp might be a more recent structure. The rotation of the stellar component is generally smaller (as expected) than the gas rotation.

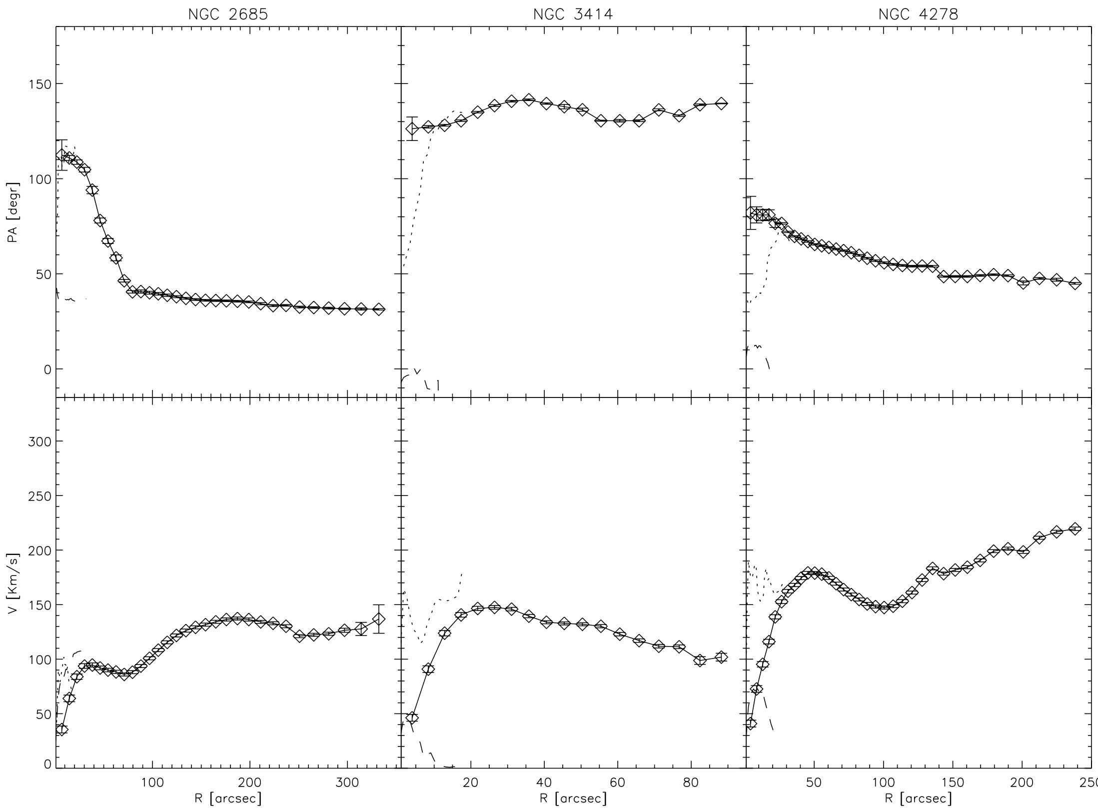

Figure 4. Radial profiles of PA (top) and projected rotation curves (bottom) of the neutral hydrogen in three galaxies that show regularly rotating structures (open symbols). For comparison, we have overplotted the same quantities for the ionized gas (dotted lines) and stars (dashed lines) as measured on the SAURON velocity maps. We subtracted 360°from the PA of the stellar component in NGC 3414 for presentation purposes.

A clear trend that is visible in our data is that *galaxies with regular H I discs also have extended, kinematically regular structures in the ionized gas*. Even NGC 2768 may fit this rule. In this galaxy a large, very regular (polar) disc of ionized gas is seen that does not have a regular neutral counterpart. Nevertheless, the H I in this galaxy seems to be an extension of the polar ionized disc, and could be the outer remains of the accretion that lead to the polar structure, so a relation between the H I and the ionized gas may exist. Conversely, the galaxies with 'offset H I clouds' have fainter emission from the ionized gas, while also this ionized gas seems to form a less regular structure. In NGC 1023, the galaxy with a large, less regular H I structure, the kinematics of the ionized gas is very similar to that of the neutral gas. In two (NGC 2549 and NGC 7457) of the three objects without H I detection, there is evidence of [O III] and Hβ emission, but this emission is very faint compared to the other cases mentioned above. NGC 5308 is the only case completely devoid of ionized gas and also no H I has been found. In NGC 5982 ionized gas is not visible in the direction of the blob (or on that side of the galaxy). Ionized gas emission is localized on the central 10 arcsec with a tail going south and the gas velocities are consistent with the redshift of the H I cloud.

5.2 Nature of the host galaxy

Our observations have revealed H I in all four galaxies classified as E in the RC3, and in five out of the eight S0s. This is perhaps surprising, as one might have naively expected that the presence of an H I disc is connected with a stellar disc, and that H I therefore would be detected more often in the S0 galaxies than in the true elliptical galaxies. This is clearly not the case. Moreover, one of the extended H I discs is found in the E galaxy NGC 4278.

The SAURON stellar kinematics shows that early-type galaxies can be classified more physically as slow- and fast rotators, based on a measure of their specific angular momentum (Emsellem et al., in preparation), with the former being fairly isotropic and mildly triaxial objects, and the latter nearly axisymmetric and radially anisotropic (Cappellari et al. 2005). Nine of our objects are fast rotators, and only three are slow rotators (NGC 3414, NGC 5198 and NGC 5982).

Fig. 5 shows the classical V/σ versus ϵ diagram for our 12 objects. The data show no trend between the detection and/or the morphology of the H I and the dynamical type of galaxy. In particular, H I is detected (including one H I disc) in all slow rotators while all the H I upper limits are found for fast rotators. More generally, H I detections are uniformly spread through the $(V/\sigma, \epsilon)$ diagram. If fast and slow rotators represent the relics of different formation paths, this does not appear in the presence and distribution of the H I.

5.3 Neutral hydrogen and stellar population

Given the evidence linking the neutral gas to ionized gas components and to evidence of accretion, it is natural to expect a link between the neutral gas content and episodes of star formation. We therefore investigate whether the luminosity-weighted age of the stellar population derived from the SAURON data (Kuntschner et al. 2006; Kuntschner et al., in preparation), within $1R_e$, using the population models by Thomas, Maraston & Bender (2003), correlates with the presence or morphology of the neutral hydrogen.

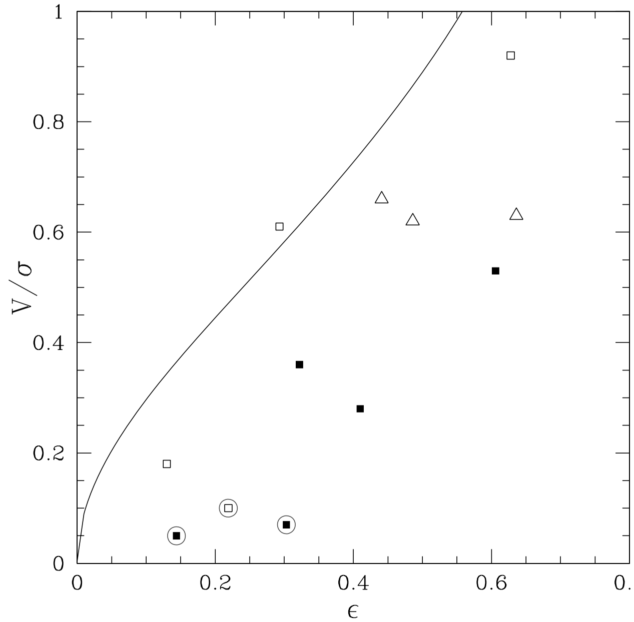

Figure 5. Ratio of ordered over random motion V/σ versus the observed flattening ϵ for the 12 objects in the sample studied in this paper (values taken from Cappellari et al., in preparation). The oblate isotropic rotator line (Binney 2005) is also shown. The H I morphology of each object is indicated by different symbols: triangle: H I upper limits; filled squares: H I offset blobs or messy; open squares: H I discs. Symbols with a circle indicate the three slow rotators.

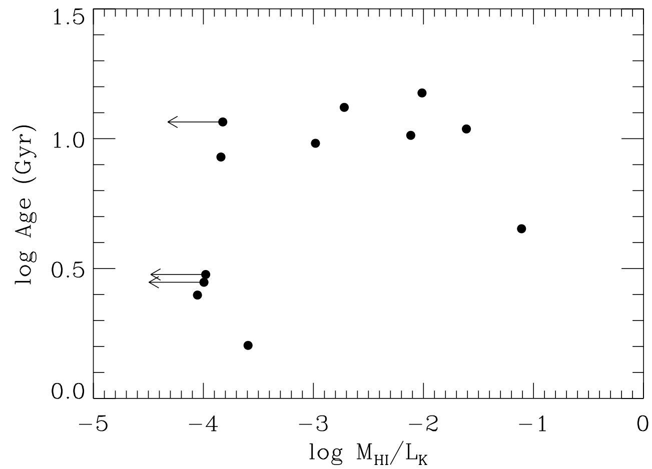

Figure 6. Estimates of the luminosity-weighted stellar age, as derived from the SAURON data within $1R_{\rm e}$ plotted against the H I mass fraction ($M_{\rm H\,I}/L_K$). Arrows indicate upper limit to the H I mass fraction in galaxies with no gas detection. We use the K-band luminosity, instead of the B band, as it is much less sensitive to dust absorption effects, and because it better traces the bulk of the dominant old stellar population of early-type galaxies.

We find that no clear trend emerges: a relatively young stellar component can be found both in galaxies detected in H I (e.g. NGC 4150) as well as in galaxies undetected (e.g. NGC 7457). Moreover, H I detected galaxies can be dominated by an old stellar population (e.g. NGC 1023, NGC 3414, NGC 4278). In particular for NGC 1023 this is remarkable as the complex kinematics of the H I in this galaxy suggests that significant accretion of gas has occurred recently.

Fig. 6 illustrates the distribution of the global stellar age versus the H I mass fraction ($M_{\rm H\,I}/L_K$). We use the K-band luminosity, instead of the B band, as it is much less sensitive to dust absorption effects, and because it better traces the bulk of the dominant old stellar population of early-type galaxies. Although the statistics is extremely limited, it is intriguing to note that galaxies with a relatively young stellar population are found among those with a low H I mass fraction. The galaxies with high H I mass fraction tend to have an old stellar component.

The typical column densities of the H I (at the modest spatial resolution of our observations) are relatively low, at most a few times 10^{20} cm^{-2}. This, therefore, confirms what was already found in other H I studies of early-type galaxies (e.g. van Driel & van Woerden 1991; Morganti et al. 1997), namely that even in the cases where a large reservoir of H I is found, the gas is spread over a large area and therefore very diluted and not able to reach, at least on large scales, a column density high enough for star formation to occur (Kennicutt 1989; Schaye 2004). This result has been taken as an indication that a large H I reservoir can stay around for a very long time without being consumed by any star-forming activity. This could mean that many systems acquire gas but that only in some this gas manages to form stars (see Fig. 6) and gets consumed while in others this is not the case. Hence, we do not find any correlation between the presence/morphology of the H I and the stellar population.

However, it is worth noting that individual cases do exist where the merger origin of the galaxy has been confirmed by the similarities between the age of the H I structures and the age of the youngest of the stellar population detected. In the H I-rich early-type galaxies IC 4200 and B2 0648+27 (Serra et al. 2006; Emonts et al. 2006b, respectively) the age of the youngest stellar population is found to be about 2 Gyr for IC 4200 and 0.3 Gyr for B2 0648+27 while the age of the H I structure derived from the regularity of the H I distribution (i.e. the neutral hydrogen must have had the time to complete 1–2 orbits) is 1–2 Gyr. Thus, both diagnostics suggest that both of these galaxies have formed between 1 and 3 Gyr ago as a result of major mergers.

Another possibility is that the neutral hydrogen comes from smooth, cool accretion of the intergalactic medium (IGM; see e.g. Keres et al. 2005, and references therein): in this case we do not expect a major star formation event that would leave a distinct marker in the stellar population as would be the case in a merger, but perhaps more continuous small episodes of star formation from the smoothly acquired gas. Therefore, a correlation between the H I amount/structures and the age of the stellar population would not necessarily be expected since the young stellar population would be small. This appears to be a realistic possibility for some of the galaxies in our sample (see also Section 7).

6 H I AND RADIO AGN

The nuclear activity in galaxies is often being explained as triggered by merger and/or interaction processes. Torques and shocks during the merger can remove angular momentum from the gas in the merging galaxies and this provides injection of substantial amounts of gas/dust into the central nuclear regions (see e.g. Mihos & Hernquist 1996). This can lead to kinematically distinct components. The presence of gas associated with most of the galaxies in our sample and the presence of kinematically complex stellar features (e.g. KDCs) suggest that at least some of the galaxies have experienced an interaction/merger in their past, and makes it interesting to explore whether any relation exists between the observed characteristics of the gas and the presence of nuclear radio emission that could be the result of an active nucleus.

We have derived for each galaxy the flux of the radio continuum (or upper limit to it) from the images obtained from the line-free channels of our line observations. In eight of the 12 galaxies the radio continuum is detected and it appears in all cases unresolved and coincident with the optical centre. The radio powers are listed in Table 2. The galaxies are (with one exception, NGC 4278) all low-power radio sources (i.e. $<10^{21}$ W Hz^{-1}, well below the typical power of radio galaxies). At these levels of emission, the radio continuum can be both due to an active nucleus or to star formation in the nuclear regions. Based on the flat spectrum typical of the radio component, a study at 3.6 cm of nearby E/S0 galaxies (with four objects in common with our sample) identified low-power AGN as the most likely source in a significant fraction of the objects (Krajnović & Jaffe 2002). In addition to this, NGC 4278 is a well-known weak radio galaxy where radio jets have been observed (Giroletti, Taylor & Giovannini 2005, and references therein) and where the radio emission is known to originate from the AGN. It is also worth noting that in most of the galaxies of our sample, the ionized gas appears to be excited by sources other than O stars (given the high [O III]/Hβ ratios), and that only in a minority of S0 galaxies has on-going star formation been observed (see also Section 5 and Sarzi et al. 2006). It is, however, still possible that different physical mechanisms could account for the weak radio continuum sources in E and S0 galaxies (e.g. Wrobel & Heeschen 1991).

Interestingly, Table 1 shows that the galaxies undetected in H I are also undetected in radio continuum (note that NGC 7332 is indicated as detection in H I but it is in fact an uncertain case as discussed in Section 3.2). The presence of a possible connection between the two (to be confirmed with a larger sample) suggests that whatever the process is that brings the neutral gas in/around these objects, it can also lead to the triggering of some activity in the nucleus.

7 ORIGIN OF THE NEUTRAL GAS

The similarities in the kinematics of the neutral and the ionized gas suggest that they are simply two phases of the same structure, which share the same origin. Based on the distribution of the kinematic misalignment between ionized gas and stars within the full SAURON sample of E and S0s, Sarzi et al. (2006) conclude that the gas cannot be all internal or all external. For fast-rotating galaxies, there is a higher incidence of corotating gas and stars, suggesting that the two are closely linked, favouring an internal origin in some cases. For slow-rotating galaxies, which tend to be rounder and more triaxial, the kinematic orientations of the stars and gas have no preferred alignment, suggesting that external accretion can explain the presence of gas in these systems.

Our H I data show, in agreement with other studies (e.g. Knapp et al. 1985), that the distribution of the ratio $M_{\rm H\,I}/L_B$ derived from our observations is very broad and the H I content is uncorrelated with the optical luminosity of the galaxy (unlike the case of spiral galaxies). This can be taken as an indication of an external origin for the gas. In addition to this argument, in a large fraction of the objects discussed in this paper, the distribution and kinematics of the H I (i.e. offset clouds/polar discs) clearly indicate an external origin. It appears, therefore, that at least small accretion events are very common in the life of every early-type galaxy. Indeed, although an internal origin of the gas cannot be completely ruled out, it is difficult to identify any of our galaxies where the origin of the H I could be *completely* internal (i.e. the result of stellar mass loss). Even in the case of NGC 4150 where most of the H I comes from a very small (galaxy-scale) disc that, in principle, could have an internal origin, very faint H I emission is also detected well outside the galaxy, while also the stellar kinematics shows the presence of a small kinematically decoupled core (composed of relatively young stars) that seems to indicate that a merger/accretion event must have occurred in the recent past of this galaxy.

While mergers and small-companion accretions appear to be at the origin of some of the observed H I structures it is, however, confusing to see that the stellar population does not reflect the presence of a younger component related to a recent merger/accretion. An extreme case is NGC 1023 where, despite the large amount of neutral hydrogen distributed in a complex and very clumpy way perhaps as a result of a recent interaction, only an old stellar population is observed. In other cases with more regular structures, the H I column densities are low so that little star formation has occurred and will occur so that the star formation triggered by the merger is a small fraction of the stellar mass and therefore difficult to detect. In most of the galaxies in our sample, the evidence, from the optical point of view, of a recent merger/interaction are quite subtle (except for NGC 2685). This may again suggest that the neutral hydrogen is able to stay around (given suitable conditions of the environment) for long periods without leading to obvious optical features. It can also indicate that instead of a merger event, the H I originates from smooth, cold accretion of IGM. The possibility of forming even polar ring structures in this way has been described in Macció et al. (2006). Indeed, this could be supported, at least for some cases, from the lack of relation between the presence of the H I and the age of the stellar population.

While steady cold accretion may work on large scales, it is not clear whether a similar mechanism can also explain the presence of central stellar decoupled components as well as the possible connection between the presence of central radio continuum and the presence of neutral hydrogen (Section 6). If this relation is confirmed by larger samples, a way to explain it is via a merger/accretion event that not only can supply the large-scale gas, but that is also able to supply a fraction of the gas to the nuclear regions. The typical time-scale of the radio emission (10^7–10^8 yr) is much shorter than the time-scale the H I can stay around (see e.g. Section 5.2), therefore, either these low-power AGN go through multiple periods of activity or the activity is triggered at a later stage of the merger (as it seems to be the case for more powerful radio galaxies, see e.g. Tadhunter et al. 2005; Emonts et al. 2006b).

8 CONCLUSIONS

The main result of these observations is that, in terms of the neutral gas, *the class of early-type galaxies is extremely rich and varied and that galaxies that prima facie appear very similar show subtle but important differences*. Our detection rate of H I (~70 per cent) is comparable to that ionized gas (75 per cent; Sarzi et al. 2006). This is surprisingly high compared with earlier studies, likely the consequence of the fact that our H I data are a factor 50–100 deeper. As with the ionized gas, we find a variety of structures, including irregular distributions (likely the remnant of a recent accretion), small polar rings, strongly warped (up to 90°) structures and extended regular discs (in some cases containing as much H I as the Milky Way!). The peak column density in these discs is low – below (and sometimes well below) a few times 10^{20} cm^{-2} – so no significant star formation is occurring, implying that these discs may survive for a very long time.

A very clear correlation exists between the presence and the properties of ionized and neutral gas. They share the same kinematics, showing that they are two phases of the same structure. On the other hand, the correlation of the gas kinematics (neutral and ionized) with that of the stars is quite poor. Most interestingly, we find that neither the amount of gas, nor its kinematics, correlate clearly with the stellar dynamics: the galaxies with slow stellar rotation (likely to be 'true' elliptical galaxies) are all detected in H I, with some containing regular gas discs. Conversely, many of the fast-rotating galaxies (likely S0-like galaxies) are not detected. This range of gas properties does not intuitively reflect the structural differences between elliptical and S0 galaxies, but suggests that the relationship between the gaseous and stellar components is more complex than previously thought.

Moreover, the amount of neutral gas *does not* appear to correlate with the stellar population characteristics. In a few galaxies, large amounts of H I are detected while the luminosity-weighted stellar population is purely old, showing no evidence of young stars that may have formed from the gas. Conversely, there are galaxies with a young luminosity-weighted age where no gas is detected. This is contrary to the commonly held idea that accretion and merging trigger star formation in the central regions. This suggests that other modes of accretion also exist, and may hint that 'cold accretion' does occur in some systems.

In the galaxies detected in H I we also detect radio continuum radiation which may be from a small AGN or result from star formation. In the H I non-detections, no such source is detected. This suggests that whatever process brings the neutral gas to early-type galaxies, it can trigger some activity/star formation in the central regions.

Our survey indicates that the presence of neutral gas is common in field early-type galaxies, if sufficiently deep observations are available. This is further supported by the fact that the observed galaxies were not selected based on any peculiarity and are relatively regular objects. Our results point to an external origin of the gas, suggesting that gas accretion is common and does not happen only in peculiar early-type galaxies. This may be connected to the high incidence of small-scale kinematical features in the SAURON data. This accretion can happen in many different ways, and can involve a very large range of masses. Also in spiral galaxies, gas accretion events are found to be very common over their lifetime (van der Hulst & Sancisi 2004; Naab & Ostriker 2006). From our study it appears that the distribution, more than the amount, of H I is an important element in determining the morphology of the galaxy. Even in the very H I-rich early-type galaxies, the neutral hydrogen is always distributed over very large areas therefore it has always a very low column density, too low for star formation to occur.

Our current sample includes only 12 galaxies restricted to low-density environments, and the statistical validity of our results is therefore limited. Given the links that seem to be present between the characteristics of the neutral and ionized gas components, it is important to re-examine also the cluster environment to fully explore the effect/importance that the environment has on our results. In cluster galaxies, the fraction of ionized gas detections – derived from the SAURON study – is about 55 per cent, and therefore, if the relation holds, a significant number of galaxies may indeed show neutral hydrogen even in this more hostile environment.

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APPENDIX A: SERENDIPITOUS DISCOVERY OF A POSSIBLE OH MEGAMASER

All the H I observations presented in this paper were carried out using the wide band (20 MHz) offered by the WSRT. This means that emission can be detected over a wide range of velocities. In the observations of NGC 4150, we have detected an emission located more than 10 arcmin from the centre of the field (i.e. NGC 4150). The observed complex spectrum is shown in Fig. A1. Two main peaks are observed (at the frequencies of ∼1428.24 and 1428.63 MHz), but the emission covers a range of at least ∼3 MHz. If the emission would originate from neutral hydrogen, it would correspond to a systemic velocity of $-1700\,\mathrm{km\,s^{-1}}$. A more realistic possibility is that the detection corresponds to an emission line different from H I.

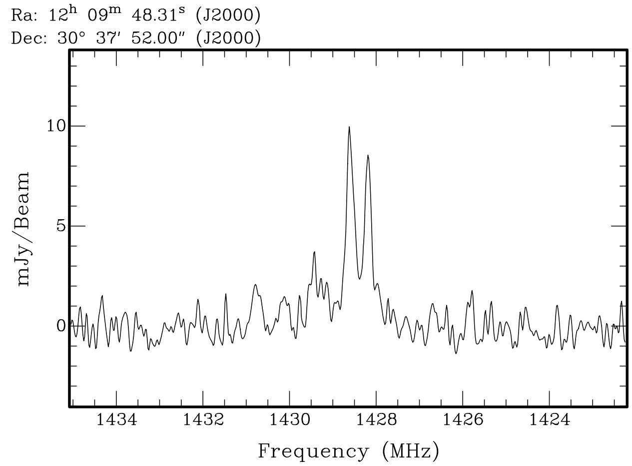

Figure A1. Spectrum of the serendipitous emission in the field of NGC 4150.

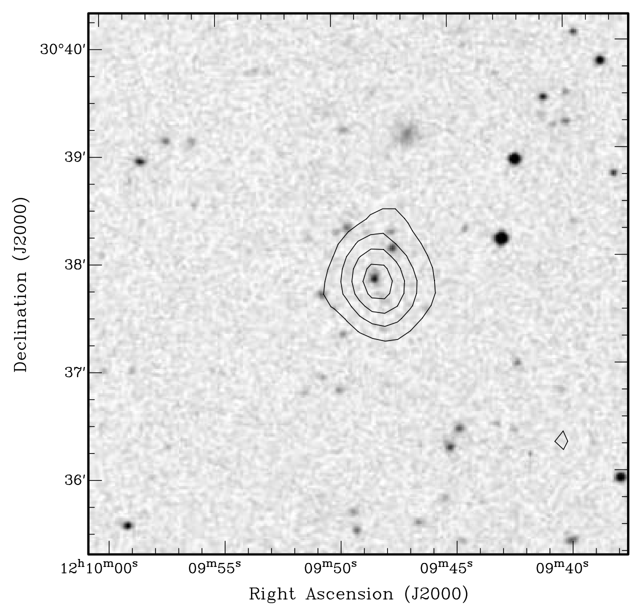

Figure A2. Total intensity of the possible detection of an OH megamaser in the field of NGC 4150.

The total intensity of the emission superimposed on to an optical image is shown in Fig. A2. As visible in the figure, the emission (located at RA = $12^{\mathrm{h}}09^{\mathrm{m}}48^{\mathrm{s}}$ and $\delta = 30°37'52''$ J2000) has an optical counterpart, also identify as the *IRAS* source *IRAS* F12072+3054. Continuum emission is also detected at the location of the line emission. The flux of the continuum is 270 μJy.

We suggest that the detected emission could originate from an OH megamaser, often found in IR bright galaxies (see e.g. Baan, Salzer & Lewinter 1998). The main lines of the hydroxyl emission are at 1665 and 1667 MHz. This would mean that the emitting galaxy is located at $z \sim 0.17$. If confirmed, this would represent the first OH megamaser discovered serendipitously with the WSRT.

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